Proc. Natl. Acad. Sci. USA
Vol. 90, pp. 4766–4773, June 1993
Colloquium Paper

This paper was presented at a colloquium entitled "Physical Cosmology," organized by a committee chaired by David N. Schramm, held March 27 and 28, 1992, at the National Academy of Sciences, Irvine, CA.

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Scientific results from the Cosmic Background Explorer (COBE)

(microwave/infrared)

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ABSTRACT **The National Aeronautics and Space Administration (NASA) has flown the COBE satellite to observe the Big Bang and the subsequent formation of galaxies and large-scale structure. Data from the Far-Infrared Absolute Spectrophotometer (FIRAS) show that the spectrum of the cosmic microwave background is that of a black body of temperature $T = 2.73 \pm 0.06$ K, with no deviation from a black-body spectrum greater than 0.25% of the peak brightness. The data from the Differential Microwave Radiometers (DMR) show statistically significant cosmic microwave background anisotropy, consistent with a scale-invariant primordial density fluctuation spectrum. Measurements from the Diffuse Infrared Background Experiment (DIRBE) provide new conservative upper limits to the cosmic infrared background. Extensive modeling of solar system and galactic infrared foregrounds is required for further improvement in the cosmic infrared background limits.**

Introduction to the COBE‖ and Mission Objectives

The observables of modern cosmology include the Hubble expansion of the universe; the ages of stars and clusters; the distribution and streaming motions of galaxies; the content of the universe (its mass density and composition and the abundances of the light elements); the existence, spectrum, and anisotropy of the cosmic microwave background (CMB) radiation; and other potential backgrounds in the infrared, ultraviolet, x-ray, γ-ray, etc. The purpose of the COBE mission is to make definitive measurements of two of these observable cosmological fossils: the CMB radiation and the cosmic infrared background (CIB) radiation. Since the discovery of the CMB in 1964 (1), many experiments have been performed to measure the CMB spectrum and spatial anisotropies over a wide range of wavelengths and angular scales. Fewer attempts have been made to conduct a sensitive search for a CIB radiation, expected to result from the cumulative emissions of luminous objects formed after the universe cooled sufficiently to permit the first stars and galaxies to form.

In 1974 NASA issued Announcements of Opportunity (AO-6 and AO-7) for new Explorer-class space missions. A proposal for a Cosmic Background Radiation Satellite was submitted by John Mather *et al.* (2) from NASA/Goddard Space Flight Center. The objectives of this mission were as follows: (*i*) make "definitive measurement of the spectrum (of the 2.7 K CBR [cosmic background radiation]) . . . with precision of 10^{-4} around the peak. . . . It will also look for the emission from cold dust clouds and from infrared galaxies"; (*ii*) "measure the large scale isotropy of the background radiation . . . to a precision of 10^{-5}. . . . Measurements at several wavelengths are required in order to distinguish anisotropy in the background radiation itself from anisotropy due to discrete sources"; and (*iii*) ". . . search for diffuse radiation in the 5–30 micron wavelength range, expected to arise from interplanetary dust, interstellar dust, and, in particular, from the integrated luminosity of very early galaxies. The experiment is designed to separate these contributions by their spectral and directional properties." Additional proposals were also submitted for large angular scale microwave isotropy experiments by Sam Gulkis *et al.* (3) from the Jet Propulsion Laboratory and by Luis Alvarez *et al.* (4) from University of California at Berkeley. NASA selected six investigators from these proposals and formed the core of what was to become the COBE Science Working Group.

The three scientific instruments on COBE are the Far Infrared Absolute Spectrophotometer (FIRAS), the Differential Microwave Radiometers (DMR), and the Diffuse Infrared Background Experiment (DIRBE). The FIRAS objective is to make a precision measurement of the spectrum of the CMB from 1 cm to 100 μm. The DMR objective is to search for CMB anisotropies on angular scales larger than 7° at frequencies of 31.5, 53, and 90 GHz. The DIRBE objective is to search for a CIB by making absolute brightness measurements of the diffuse infrared radiation in 10 photometric bands from 1 to 240 μm and polarimetric measurements from 1 to 3.5 μm. The FIRAS and DIRBE instruments are located inside a 650-liter superfluid liquid helium Dewar. A full description of the COBE emission is given by Boggess *et al.* (5). Many papers giving overviews, implications, and additional detailed information about the COBE have been presented (6–17).

Spectral Results from FIRAS

Spectrum of the Primeval Radiation. The discovery of the CMB radiation by Penzias and Wilson (1) provided strong

Abbreviations: COBE, Cosmic Background Explorer; CMB, cosmic microwave background; CIB, cosmic infrared background; NASA, National Aeronautics and Space Administration; FIRAS, Far Infrared Absolute Spectrophotometer; DMR, Differential Microwave Radiometers; DIRBE, Diffuse Infrared Background Experiment; CL, confidence limit; IRAS, Infrared Astronomical Satellite.

‖The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the COBE. Scientific guidance is provided by the COBE Science Working Group. GSFC is also responsible for the development of the analysis software and for the production of the mission data sets.

evidence for Big Bang cosmology. Radiation produced in the very early universe was frequently scattered until about 300,000 years after the Big Bang. At this point, the "recombination," the characteristic energy in the universe fell to the point where previously free electrons could combine with nuclei to form neutral atoms. The 2.7-K radiation we see today has been traveling to us unimpeded since that time. The rapid production and destruction of photons within the first year after the Big Bang forced the radiation to have a Planck (black-body) spectrum. Any mechanism that injected energy into the Universe (e.g., a particle decay) between a year after the Big Bang and ≈2000 years after the Big Bang would give rise to a radiation spectrum characterized by a nonzero chemical potential. Thus there would be a Bose–Einstein spectral distortion with the photon occupation number

$$N(\varepsilon) \approx \frac{1}{e^{(\varepsilon-\mu)/kT}-1}, \qquad [1]$$

where ε is the photon energy, μ is the chemical potential, k is the Boltzmann constant, and T is the absolute temperature. A Compton distortion is usually parameterized in terms of a Compton y-parameter,

$$y = \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c^2}\int n_{\mathrm{e}}k(T_{\mathrm{e}}-T_{\mathrm{CMB}})c\,dt, \qquad [2]$$

where σ_{T} is the Thomson scattering cross section, m_{e} is the mass of an electron, c is the velocity of light, and the integral is the electron pressure along the line of sight. A Compton distortion of the spectrum can become important when $(1+z)dy/dz > 1$, which occurs ≈2000 years after the Big Bang. The thermodynamic temperature distortion observed at a frequency ν is

$$\frac{\delta T}{T} \approx y\left(x\frac{e^x+1}{e^x-1}-4\right), \qquad [3]$$

where $x = h\nu/kT_{\mathrm{CMB}}$ and h is the Planck constant. After recombination it becomes nearly impossible to distort the CMB spectrum short of reionizing the Universe. Thus a perfect Planck CMB spectrum would support the prediction of the simplest Big Bang model of the universe, while spectral distortions would indicate the existence of more complicated releases of energy.

The FIRAS Instrument. The FIRAS instrument is a polarizing Michelson interferometer (18, 19) with two separate spectral channels. The low-frequency channel, extending from 0.5 mm to 1 cm, was designed to obtain a precise comparison between the CMB spectrum and a Planckian calibration spectrum. The objective was to attain, in each 5% wide spectral element and each 7° pixel, an accuracy and sensitivity of $\nu I_\nu \approx 10^{-9}$ W·m^{-2}·sr^{-1}, which is 0.1% of the peak brightness of a 2.7-K black body. The high-frequency channel, with a useful spectral range from 0.12 mm to 0.5 mm, was designed to measure the emission from dust and gas in our galaxy and to remove the effect of galactic radiation on the measurements of the CMB made in the low-frequency channel.

The FIRAS uses a multimode flared horn (20) with a 7° beam. The instrument directly measures the difference between the sky signal in its beam and that from a temperature-controlled internal reference body. The best apodized spectral resolution is 0.2 cm^{-1} (6 GHz). The in-orbit absolute calibration of FIRAS was accomplished by inserting an external black-body calibrator periodically into the mouth of the horn. The calibrator is a precision temperature-controlled black body, with an emissivity greater than 0.999. The FIRAS uses bolometric detectors (21–23) in both hands.

In 10 months of cryogenic operation the FIRAS obtained over two million interferograms. This complete data set is now undergoing careful analysis.

FIRAS Results. Analysis of the FIRAS data to date confirm the prediction of the simplest Big Bang model that the CMB must have a thermal spectrum. Initial results based on only 9 min of data showed that there is no deviation from a black-body spectrum $B_\nu(T)$ as large as 1% of the peak brightness (19, 24) over the spectral range from 500 μm to 1 cm. The temperature of the CMB in the direction of the north galactic pole is 2.735 ± 0.060 K, where 60 mK is the initial conservative uncertainty in the calibration of the thermometry of the absolute calibrator. These data also ruled out the existence of a hot smooth intergalactic medium that could emit more than 3% of the observed x-ray background. The thermal character of the CMB spectrum was subsequently confirmed by Gush *et al.* (25), who obtained virtually the same temperature over the spectral range 2–30 cm^{-1}. Neither mean CMB temperature quoted above is corrected for the dipole distortion. These experiments found no submillimeter excess as previously reported by Matsumoto *et al.* (26).

More recently, Shafer *et al.* (27) and Cheng *et al.* (28) have examined FIRAS spectra in a direction known previously to be very low in interstellar material (l = 142°, b = 55°). In this direction, known as Baade's Hole, the temperature is 2.730 ± 0.060 K and there is no deviation from a black-body spectrum greater than 0.25% of the peak brightness. The lack of deviations from a Planck spectrum translates to a limit on a chemical potential (see Eq. 1) of $\mu/kT < 0.005$ [95% confidence limit (CL)] and a limit on the Compton y-parameter (Eq. 2) of $y < 0.0004$ (95% CL). These results rule out a hot smooth intergalactic medium that could emit more than 1% of the observed x-ray background.

The dipole anisotropy of the CMB, presumed due to our peculiar motion relative to the Hubble flow, can be seen clearly in the FIRAS data and is consistent with previous results (29). The FIRAS data show for the first time that the difference in spectra between the poles of the dipole is that expected from two Doppler-shifted black-body curves. This result also indicates that the stability of the FIRAS instrument is better than 1 part in 5000 over long time scales. The dipole amplitude measured by FIRAS is 3.31 ± 0.05 mK in the direction l = 266° ± 1°, b = 47.5° ± 0.5°.

FIRAS results also include the first nearly all-sky, unbiased, far-infrared survey of the galactic emission at wavelengths greater than 102 μm (30). Wright *et al.* (30) present a map of the dust emission across the sky from the COBE FIRAS experiment. The total far-infrared luminosity of the galaxy is inferred to be (1.8 ± 0.6) × 10^{10} $L_\odot$, where $L_\odot$ is solar luminosity.

Wright *et al.* (30) report that spectral lines from interstellar C, C^+, and N^+ and CO molecules are detected in the mean galactic spectrum, $g(\nu)$. The lines of [C II] at 158 μm and [N II] at 205.3 μm were sufficiently strong to be mapped. This is the first observation of the 205.3-μm line. Wright *et al.* interpret the [C II] line as coming from photodissociation regions and the [N II] lines as partially arising from a diffuse warm ionized medium and partially arising from dense H II regions. Petuchowski and Bennett (31) further elaborate on this conclusion by apportioning the [C II] and [N II] transition line intensities among various morphologies of the interstellar medium. S. J. Petuchowski and C.L.B. (unpublished work) have conducted observations on NASA's Kuiper Airborne Observatory to measure the scale height of the 205.3-μm [N II] line with a much higher angular resolution (≈1 arcmin) than FIRAS.

DMR: Microwave Anisotropy Measurements and Interpretations

Primordial gravitational potential fluctuations at the surface of last scattering give rise to the distribution and motions of

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galaxies and to large angular scale fluctuations in the CMB (32). In inflationary models of cosmology (33–35) the gravitational energy fluctuations arise from quantum mechanical fluctuations from 10^{-35} s after the Big Bang that inflate to become classical fluctuations with a nearly scale invariant power spectrum (36–39).

The large angular scale CMB temperature anisotropy ΔT and gravitational potential fluctuations at the surface of last scattering $\Delta\Phi$ are simply related by $3\Delta T/T = \Delta\Phi/c^2$ for adiabatic fluctuations in a universe with no cosmological constant ($\Lambda = 0$). On much smaller scales than the DMR measures ($\theta < 4°$), i.e., on scales in causal contact with one another after the universe became matter dominated, the gravitational potential fluctuations are affected by the growth of structures through gravitational instability (40).

Measurements of the abundances of the light elements together with nucleosynthesis calculations (41, 42) imply that $0.011 \leq \Omega_B h^2 \leq 0.037$, where Ω_B is the fraction of the critical mass density ($\rho_c = 3H_0^2/8\pi G = 1.88h^2 \times 10^{-29}$ g·cm^{-3}) in baryons, where H_0 is the Hubble constant and $h = H_0/100$ km·s^{-1}·Mpc^{-1} [1 megaparsec (Mpc) = 3.09×10^{22} m]. G is Newton's constant. Inflation requires that $\Omega_0 + \Lambda_0/3H_0^2 = 1$ so that $\Lambda_0 \neq 0$, or inflation theory is incorrect, or most of the mass in the universe is yet to be detected nonbaryonic material. It is useful to assume that this nonbaryonic material does not interact with light. This simultaneously explains why it is not seen and allows it to begin clustering while the universe was radiation dominated, earlier than is possible for the baryonic matter. The nonbaryonic material is broadly categorized as "hot" or "cold" dark matter, depending on whether it was or was not relativistic when the universe became matter dominated. A neutrino with mass is a favorite hot dark matter candidate. A successful model of cosmology and the evolution of structure must match the amplitude and spectrum of density fluctuations from the galaxy scale to the horizon scale. Holtzman (43) presents the results of calculations for 94 cosmological models. Several observables have been derived from galaxy surveys, including the two-point correlation function, the amplitude of its integral, the rms mass fluctuation in a fixed radius sphere, and rms galaxy streaming velocities.

Hence, measurements of large-scale (i.e., primordial) CMB anisotropies can provide the observational link between the production of gravitational potential fluctuations in the early universe and the observed galaxy distributions and velocities today. Large-scale CMB anisotropy measurements provide both the amplitude and the power spectrum of the primordial fluctuations. Large-scale anisotropy measurements are usually expressed in terms of a multipole expansion and a correlation function. The multipole expansion is

$$T(\theta, \phi) = \sum_l \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi), \qquad [4]$$

where $Y_{lm}(\theta, \phi)$ are the spherical harmonic functions. Since DMR is a differential experiment, as are almost all anisotropy experiments, the $l = 0$ monopole terms is not observed. (It is observed by FIRAS.) The $l = 1$ dipole term is also dropped, since it is dominated by the Doppler effect due to our local peculiar velocity and not by cosmic perturbations. Thus the $l = 2$ quadrupole term is the first term of interest. We are at liberty to select any coordinate system we choose. Since galactic emission dominates the sky signal, we choose galactic coordinates to rewrite the five $Y_{l=2,m}$ components:

$$\begin{aligned} Q(l, b) = {} & Q_1(3\sin^2 b - 1)/2 + Q_2 \sin 2b \cos l \\ & + Q_3 \sin 2b \sin l + Q_4 \cos^2 b \cos 2l \\ & + Q_5 \cos^2 b \sin 2l, \end{aligned} \qquad [5]$$

where the rms quadrupole amplitude is

$$Q_{\rm rms}^2 = \frac{1}{4\pi}\int_{4\pi} Q^2(l, b)\,d\Omega = \frac{4}{15}\left(\frac{3}{4}Q_1^2 + Q_2^2 + Q_3^2 + Q_4^2 + Q_5^2\right). \qquad [6]$$

There is a small kinematic quadrupole, $Q_{\rm rms} = 1.2\ \mu$K, from the second-order terms in the relativistic Doppler expansion (44), for which (Q_1, Q_2, Q_3, Q_4, Q_5) = 0.9, −0.2, −2.0, −0.9, 0.2) μK.

The measured correlation function determines the parameters of the fluctuation power spectrum. The correlation function is

$$C(\alpha) = \sum_{l \geq 2} \Delta T_l^2 W(l)^2 P_l(\cos\alpha), \qquad [7]$$

where P_l are Legendre polynomials, and a 3.2° rms Gaussian beam gives a weighting $W(l) = \exp[-1/2(l(l+1)/17.8^2)]$ and

$$\Delta T_l^2 = \frac{1}{4\pi}\sum_m |a_{lm}|^2 \qquad [8]$$

are the rotationally-invariant rms multipole moments. As with the spherical harmonic expansion, the $l = 0$ term is excluded from the correlation function since it is not measured by differential instruments, and the $l = 1$ term is excluded because it is contaminated by the kinematic dipole. The $l = 2$ quadrupole term is sometimes excluded since the quadrupole has $2l + 1 = 5$ degrees of freedom and thus has an intrinsically high statistical or "cosmic" variance, independent of the measurement. The $l = 2$ term is also significantly affected by galactic emission. For a power law primordial fluctuation spectrum the predicted moments, as a function of spectral index $n < 3$, are given by Bond and Efstathiou (40):

$$\langle \Delta T_l^2 \rangle = (Q_{\rm rms})^2 \frac{(2l+1)}{5} \frac{\Gamma(l + (n-1)/2)\Gamma((9-n)/2)}{\Gamma(l + (5-n)/2)\Gamma((3+n)/2)}. \qquad [9]$$

For $n = 1$ this simplifies to

$$\langle \Delta T_l^2 \rangle = (Q_{\rm rms})^2 \frac{6}{5} \frac{2l+1}{l(l+1)}. \qquad [10]$$

Smoot *et al.* (45) presented preliminary DMR results based on 6 months of data. Smoot *et al.* (46) describe results based upon the first year of DMR data, Bennett *et al.* (47) describe the calibration procedures, Kogut *et al.* (48) discuss the treatment of systematic errors, and Bennett *et al.* (49) discuss the separation of cosmic and galactic signals. Wright *et al.* (50) compare these data to other measurements and to models of structure formation through gravitational instability. Previously published large-angular-scale anisotropy measurements include those of Fixsen *et al.* (51), Lubin *et al.* (52), Klypin *et al.* (53), and Meyer *et al.* (54). Some excellent reviews of CMB anisotropy and cosmological perturbation theory are provided in refs. 55–61.

The DMR Instrument and Data Processing. The COBE DMR instrument is described by Smoot *et al.* (62). DMR operates at three frequencies: 31.5, 53, and 90 GHz (wavelengths of 9.5, 5.7, and 3.3 mm), chosen to be near the minimum in galactic emission and near the CMB maximum. Wright *et al.* (63) have used the FIRAS and DMR data to show that the ratio of the galactic emission to that of the CMB reaches a minimum between 60 and 90 GHz. There are two nearly independent channels, A and B, at each frequency. The orbit and pointing of the COBE result in a complete survey of the sky every 6 months while shielding the DMR from terrestrial and solar radiation (5).

The DMR measures the difference in power received between regions of the sky separated by 60°. For each radiometer channel a baseline is subtracted and the data are calibrated. Data are rejected when the limb of the Earth is higher than 1° below the Sun/Earth shield plane, when the Moon is within 25° of a beam center, when any datum deviates from the daily mean by more than 5σ, or when the spacecraft telemetry or attitude solution is of poor quality. Small corrections are applied to remove the estimated emission from the Moon and Jupiter in the remaining data. Corrections are also applied to remove the Doppler effects from the spacecraft's velocity about the Earth and the Earth's velocity about the solar system barycenter. A least-squares minimization is used to fit the data to spherical harmonic expansions and to make sky maps with 6144 nearly equal-area pixels using a sparse matrix technique (9, 64). The DMR instrument is sensitive to external magnetic fields. Extra equations are included in the sparse matrix to allow these magnetic susceptibilities to be fit separately as a linear function of the Earth's field and the radiometer orientation. The magnetic corrections are on the scale of 10 to 100 μK in the time-ordered data. Residual uncertainties in the individual radiometer channel maps, after correction, are typically 2 μK and never more than 8.5 μK.

Kogut *et al.* (48) have searched the DMR data for evidence of residual systematic effects. The largest such effect is the instrument response to an external magnetic field. Data binned by the position of the Earth relative to the spacecraft show no evidence for contamination by the Earth's emission at the noise limit (47 μK at 95% CL). The contribution of the Earth's emission to the maps is estimated to be less than 2 μK. The time-ordered data with antenna beam centers more than 25° away from the Moon are corrected to an estimated accuracy of 10% (4 μK) of the lunar flux. The estimated residual effect on the maps is less than 1 μK. Kogut *et al.* (48) list upper limits for the effects of variations in calibration and instrument baselines, solar and solar system emissions, radio frequency interference, and data analysis errors. The quadrature sum of all systematic uncertainties in a typical map, after corrections, is <8.5 μK for rms sky fluctuations, <3 μK for the quadrupole and higher-order multipole moments, and <30 μK^2 for the correlation function (all limits 95% CL).

DMR Anisotropy. The DMR maps are dominated by the dipole anisotropy and the emission from the galactic plane. The dipole anisotropy ($\Delta T/T \approx 10^{-3}$) is seen consistently in all channels with a thermodynamic temperature amplitude 3.36 ± 0.1 mK in the direction $l = 264.7° \pm 0.8°$, $b = 48.2° \pm 0.5°$, consistent with the FIRAS results, above. Our motion with respect to the CMB (a black-body radiation field) is assumed to produce the dipole anisotropy, so the dipole and associated $\approx$1.2-μK rms kinematic quadrupole are removed from the maps.

The DMR instrument noise and the intrinsic fluctuations on the sky are independent and thus add in quadrature to give the total observed signal variance

$$\sigma^2_{\rm obs} = \sigma^2_{\rm DMR} + \sigma^2_{\rm Sky}. \qquad [11]$$

The $\sigma_{\rm obs}$ is estimated from the two-channel (A + B)/2 sum maps, and the (A − B)/2 difference maps provide an estimate of $\sigma_{\rm DMR}$, yielding the sky variance $\sigma_{\rm Sky}(10°) = 30 \pm 5$ μK for $|b| > 20°$. The observations are made with a 7° beam, and the resulting maps are smoothed with an additional 7° Gaussian function, resulting in the effective 10° angular resolution.

The correlation function, $C(\alpha)$, is the average product of temperatures separated by angle α. It is calculated for each map by rejecting all pixels within the galactic latitude band $|b| < 20°$; removing the mean, dipole, and quadrupole from the remaining pixels by a least-squares fit; multiplying all possible pixel pair temperatures; and averaging the results into 2.6° bins. Bennett *et al.* (49) conclude that the galactic contribution to the correlation signal is small for $|b| > 15°$. This is consistent with the fact that the correlation function and rms sky fluctuation are insensitive to the galactic latitude cut angles so long as $|b| < 15°$ is excluded. The DMR correlation functions exhibit temperature anisotropy on all scales greater than the beam size (7°) and differ significantly ($>7\sigma$) from the flat correlation function due to receiver noise alone.

All six channels show a statistically significant quadrupole signal. A comparison of the fitted quadrupoles between channels and frequencies, and between the first and second 6 months of data, shows that individual quadrupole components, Q_i, typically differ from map to map by $\approx$10 μK with comparable uncertainty. Determination of the cosmic quadrupole is linked to its separation from galactic emission (49), summarized below. Discrete extragalactic sources individually contribute less than 2 μK in the DMR beam and the expected temperature variations are less than 1 μK (65).

Separation of Galactic Signals and the Cosmic Quadrupole. The DMR anisotropy maps are sufficiently sensitive and free from systematic errors that our knowledge of galactic emission is a limiting factor in interpreting the measurements of the 1-year DMR maps. The detected signals expressed in thermodynamic temperature are nearly constant amplitude: the rms fluctuations on a 10° scale are proportional to $\nu^{-0.3\pm1}$ and the quadrupole and correlation functions are proportional to $\nu^{-0.2\pm1}$. The flat spectral index of the DMR anisotropy, without correction of galactic emissions, is consistent with a cosmic origin and inconsistent with an origin from a single galactic component. However, from this fact alone we are unable to rule out a correlated superposition of dust, synchrotron, and free-free emission and thus more detailed galactic emission models are required. Bennett *et al.* (49) constructed preliminary models of microwave emission from our Galaxy based on COBE and other data for the purpose of distinguishing cosmic and galactic signals.

Four emission components are important at microwave wavelengths. CMB anisotropies are assumed to produce differences in the measured antenna temperature according to $\Delta T_A = \Delta T\, x^2 e^x/(e^x - 1)^2$, where $x = h\nu/kT$. Synchrotron emission arises from relativistic electrons accelerated by magnetic fields. Free-free emission occurs when free electrons are accelerated by interactions with ions. Thermal emission from dust is also important at microwave wavelengths.

The brightest pixels in the DMR maps are $T_A = 5.9 \pm 0.4$ mK at 31.5 GHz, 1.9 ± 0.2 mK at 53 GHz, both at $(l, b) = (337°, -1°)$, and 1.3 ± 0.2 mK (348°, +1°) at 90 GHz. Galactic plane emission would have to be removed to better than 1% to reveal cosmologically interesting fluctuations in the CMB at low galactic latitudes, so our preliminary models concentrate on $|b| > 10°$.

Bennett *et al.* (49) present three approaches to modeling the galactic emission signal in the DMR maps. These three approaches produce consistent results, and the cosmic signal is largely unaffected by the galactic model subtraction. Bennett *et al.* conclude that no known galactic emission component or superposition of components can account for most of the observed anisotropy signal. In the absence of significant extragalactic source signals or systematic errors, as argued above, this signal must be intrinsic to the CMB radiation.

DMR maps, with the modeled galactic emission removed, are fit for a quadrupole distribution. Bennett *et al.* (49) derive a cosmic quadrupole, corrected for the expected kinematic quadrupole, of $Q_{\rm rms} = 13 \pm 4$ μK, $(\Delta T/T)_Q = (4.8 \pm 1.5) \times 10^{-6}$, for $|b| > 10°$. When galactic emission is removed from

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the DMR data, the residual fluctuations are virtually unaffected, and therefore they are not dominated by any known galactic emission component(s).

Interpretation of the DMR Anisotropy. The anisotropy detected by the DMR is interpreted as being a direct result of primordial fluctuations in the gravitational potential. Assuming a power spectral density of density fluctuations of the form $P(k) = Ak^n$, the best-fit results are $n = 1.1 \pm 0.5$ with $Q_{\mathrm{rms-PS}} = 16 \pm 4$ μK. $Q_{\mathrm{rms-PS}}$ is the rms quadrupole amplitude resulting from this power spectrum fit—i.e., making use of fluctuation information from all observed angular scales, as opposed to the Q_{rms} derived from a direct quadrupole fit. Forcing the spectral index to $n = 1$ gives $Q_{\mathrm{rms-PS}} = 16.7 \pm 4$ μK and increases the χ^2 from 79 to 81 for 68 degrees of freedom. Interpreted as a power-law spectrum of primordial fluctuations with a Gaussian distribution, the ΔT_l^2 in each horizon have a χ^2 distribution of $2l + 1$ degrees of freedom, giving a cosmic variance for observations within a single horizon volume of $2\langle\Delta T_l^2\rangle^2/2(2l + 1)$. Best-fit values are $n = 1.15^{+0.45}_{-0.65}$ and $Q_{\mathrm{rms-PS}} = 16.3 \pm 4.6$ μK including the cosmic variance, with a χ^2 of 53. Cross-correlation of the 53-GHz and 90-GHz maps is consistent with a power law spectrum with index $n = 1 \pm 0.6$ and amplitude $Q_{\mathrm{rms-PS}} = 17 \pm 5$ μK, including cosmic variance.

The observed cosmic quadrupole from the maps [$Q_{\mathrm{rms}} = 13 \pm 4$ μK from Bennett *et al.* (49) (see above)] is slightly below the mean value predicted by the higher-order moments deduced from the correlation function ($Q_{\mathrm{rms-PS}} = 16 \pm 4$ μK). This is a likely consequence of cosmic variance: the mode of the χ^2 distribution is lower than the mean. A map quadrupole value of 13 μK or lower would be expected to occur 35% of the time for an $n = 1$ universe with $Q_{\mathrm{rms-PS}} = 16$ μK. The results above exclude the quadrupole before computing $C(\alpha)$. Including the quadrupole when $C(\alpha)$ is computed increases the χ^2, raises n to 1.5, and decreases $Q_{\mathrm{rms-PS}}$ to 14 μK.

The measured parameters [$\sigma_{\mathrm{Sky}}(10°)$, Q_{rms}, $Q_{\mathrm{rms-PS}}$, $C(\alpha)$, and n] are consistent with a Peebles–Harrison–Zeldovich (scale-invariant) spectrum of perturbations, which predicts $Q_{\mathrm{rms}} = (1^{+0.3}_{-0.4})Q_{\mathrm{rms-PS}}$ and $\sigma_{\mathrm{Sky}}(10°) = (2.0 \pm 0.2)Q_{\mathrm{rms-PS}}$. The theoretical 68% CL errors take into account the cosmic variance due to the statistical fluctuations in perturbations for our observable portion of the Universe. The minimum Q_{rms} for models with an initial Peebles–Harrison–Zeldovich perturbation, normalized to the local large-scale galaxy streaming velocities, is predicted to be 12 μK, independent of the Hubble constant and the nature of dark matter (66, 67).

These observations are consistent with inflationary cosmology models. The natural interpretation of the DMR signal is the observation of very large (presently $>>$100 Mpc) structures in the Universe which are little changed from their primordial state ($t << 1$ s). These structures are part of a power-law spectrum of small-amplitude gravitational potential fluctuations that on smaller length scales are sources of the large-scale structure observed in the Universe today. The DMR data provide strong support for gravitational instability theories (50). Wright *et al.* (50) compare the 94 cosmological models from Holtzman (43) with the DMR anisotropy results. None of the Holtzman isocurvature models are compatible with the DMR anisotropy amplitude for a biasing factor $b < 4$. Wright *et al.* find that three Holtzman models fit the observational data (galaxy clustering, galaxy streaming velocity, and CMB quadrupole amplitude) reasonably well. These models are described below.

A model with vacuum energy density with $\Omega_{\mathrm{vac}} = \Lambda/3H_0^2 = 0.8$, $H_0 = 100$ km·s^{-1}·Mpc^{-1}, $\Omega_{\mathrm{B}} = 0.02$, $\Omega_{\mathrm{CDM}} = 0.18$ is an excellent fit to the observational data (see, e.g., refs. 68–71).

A "mixed dark matter" (MDM) model that fits the data uses both hot dark matter (a massive neutrino with $\Omega_{\mathrm{HDM}} = 0.3$) and cold dark matter ($\Omega_{\mathrm{CDM}} = 0.6$) with baryonic dark matter $\Omega_{\mathrm{B}} = 0.1$ and $H_0 = 50$ km·s^{-1}·Mpc^{-1}. See, e.g., refs. 69, 72, and 73 for further recent discussions of mixed dark matter models.

An open-universe model with $\Omega_0 = 0.2$, $\Omega_{\mathrm{B}} = 0.02$, and $\Omega_{\mathrm{CDM}} = 0.18$ for $H_0 = 100$ km·s^{-1}·Mpc^{-1} satisfies the observations, except perhaps for the galaxy rms peculiar velocities, but is in conflict with the inflation model and theoretical prejudices for $\Omega_0 = 1$ (see refs. 70, 71, and 74).

The unbiased standard cold dark matter is in conflict with galaxy clustering data, even without the constraint of the COBE data (e.g., refs. 75 and 76). Hogan (77–79) and Hoyle and Burbidge (80) interpret the COBE-DMR results in terms of models where the temperature anisotropies do not arise from gravitational potential fluctuations on the surface of last scattering. Bennett and Rhie (81) interpret the DMR data in terms of global monopoles and textures.

In summary, the COBE detection of CMB temperature anisotropy has added another important observational piece of knowledge to the cosmic puzzle. There is not yet a clear favorite among the models that attempt to account for all of the pieces, nor is there likely to be one without further observational information.

DIRBE

CIB Radiation. The DIRBE is the first space experiment designed primarily to measure the CIB radiation. The aim of the DIRBE is to conduct a definitive search for an isotropic CIB radiation, within the constraints imposed by the local astrophysical foregrounds.

Cosmological motivations for searching for an extragalactic infrared background have been discussed in the literature for several decades (early papers include refs. 82–86). Both the cosmic redshift and reprocessing of short-wavelength radiation to longer wavelengths by dust act to shift the short-wavelength emissions of cosmic sources toward or into the infrared. Hence, the wide spectral range from 1 to 1000 μm is expected to contain much of the energy released since the formation of luminous objects, and it could potentially contain a total radiant energy density comparable to that of the CMB.

The CIB radiation has received relatively little attention in the theoretical literature compared with that devoted to the CMB (87), which has a central significance to Big Bang cosmology and quite distinctive and definite predictions as to its character. However, advances in infrared instrumentation, and especially the introduction of cryogenically cooled infrared instruments on space missions, have stimulated increasing attention to prediction of the character of the CIB radiation (88–93). Measurement of the spectral intensity and anisotropy of the CIB radiation would provide important new insights into intriguing issues such as the amount of matter undergoing luminous episodes in the pregalactic Universe, the nature and evolution of such luminosity sources, the nature and distribution of cosmic dust, and the density and luminosity evolution of infrared-bright galaxies.

Observing the CIB radiation is a formidable task. Bright foregrounds from the atmosphere of the Earth, from interplanetary dust scattering of sunlight and emission of absorbed sunlight, and from stellar and interstellar emissions of our own Galaxy dominate the diffuse sky brightness in the infrared. Even when measurements are made from space with cryogenically cooled instruments, the local astrophysical foregrounds strongly constrain our ability to measure and discriminate an extragalactic infrared background. Furthermore, since the absolute brightness of the CIB radiation is of paramount interest for cosmology, such measurements must be done relative to a well-established absolute flux reference with instruments that strongly exclude, or permit discrimination of, all stray sources of radiation or offset signals which could mimic a cosmic signal.

Hauser (13) lists recent experiments capable of making absolute sky brightness measurements in the infrared (for a compilation including some earlier measurements, see ref. 87). Instruments or detector channels designed specifically to measure that part of the spectrum dominated by the CMB radiation have been excluded. Murdock and Price (94) flew an absolute radiometer with strong stray light rejection on a sounding rocket in 1980 and 1981. Their primary objective was measuring scattering and emission from interplanetary dust, and no attempt was made to extract an extragalactic component. Matsumoto *et al.* (95) flew a near-infrared experiment on a rocket in 1984. They have reported possible evidence for an isotropic residual near 2 μm, perhaps in a line feature, for which they cannot account in their models of emission from the interplanetary medium and the Galaxy. This group has flown a modified instrument early in 1990 to investigate further this result (96). The Infrared Astronomical Satellite (IRAS) sky survey instrument, though not specifically designed for absolute background measurements, was, within the limits of long-term stability, capable of good relative total sky brightness measurements, and so is included in this list. Uncertainties in the IRAS absolute calibration have impeded efforts to extract an estimate of the CIB radiation (97). The FIRAS high-frequency channel (100–500 μm), with its all-sky coverage, excellent stray light rejection, absolute calibration, and high sensitivity, also promises to be an important instrument for CIB radiation studies. Quantitative comparison of the measurements from the experiments discussed above and a summary of current CIB radiation limits are discussed further below.

The DIRBE Instrument. The experimental approach is to obtain absolute brightness maps of the full sky in 10 photometric bands (J[1.2], K[2.3], L[3.4], and M[4.9]; the four IRAS bands at 12, 25, 60, and 100 μm; and 140- and 240-μm bands). To facilitate discrimination of the bright foreground contribution from interplanetary dust, linear polarization is also measured in the J, K, and L bands, and all celestial directions are observed hundreds of times at all accessible angles from the Sun in the range 64° to 124°. The instrument rms sensitivity per field of view in 10 months is λI_λ = (1.0, 0.9, 0.6, 0.5, 0.3, 0.4, 0.4, 0.1, 11.0, 4.0) × 10^{-9} W·m^{-2}·sr^{-1}, respectively, for the 10 wavelength bands listed above. These levels are generally well below both estimated CIB radiation contributions (e.g., ref. 89) and the total infrared sky brightness.

The DIRBE instrument is an absolute radiometer, utilizing an off-axis Gregorian telescope with a 19-cm-diameter primary mirror. Since the DIRBE was designed to make an absolute measurement of the spectrum and angular distribution of the diffuse infrared background, it must have extremely strong rejection of stray light. The optical configuration (98) has strong rejection of stray light from the Sun, Earth limb, Moon or other off-axis celestial radiation, or parts of the COBE payload (99, 100). Stray light rejection features include both a secondary field stop and a Lyot stop, superpolished primary and secondary mirrors, a reflective forebaffle, extensive internal baffling, and a complete light-tight enclosure of the instrument within the COBE Dewar. Additional protection is provided by the Sun and Earth shade surrounding the COBE Dewar, which prevents direct illumination of the DIRBE aperture by these strong local sources. The DIRBE instrument, which was maintained at a temperature below 2 K within the Dewar as long as helium was present, measures absolute brightness by chopping between the sky signal and a zero-flux internal reference at 32 Hz, using a tuning fork chopper. The synchronously demodulated signal is averaged for 0.125 s before transmission to the ground. Instrumental offsets are measured by closing a cold shutter located at the prime focus. All spectral bands view the same instantaneous field of view, 0.7° × 0.7°, oriented at 30° from the spacecraft spin axis. This allows the DIRBE to modulate the angle from the Sun by 60° during each rotation, and to sample fully 50% of the celestial sphere each day. Four highly reproducible internal radiative reference sources can be used to stimulate all detectors when the shutter is closed to monitor the stability and linearity of the instrument response. The highly redundant sky sampling and frequent response checks provide precise photometric closure over the sky for the duration of the mission. Calibration of the photometric scale is obtained from observations of isolated bright celestial sources. Careful measurements of the beam shape in preflight system testing and during the mission using scans across bright point sources allow conversion of point-source calibrations to surface brightness calibrations.

2

The data obtained during the helium temperature phase of the mission are of excellent photometric quality, showing good sensitivity, stability, linearity, and stray light immunity. Few artifacts are apparent other than those induced by energetic particles in the South Atlantic Anomaly and variations in instrument temperature. Both of these effects will be removed in final data processing. Strong rejection of off-axis radiation sources is confirmed by the absence of response to the Moon (which saturates the response in all detectors when in the field of view) until it comes within about 3° of the field of view. The sensitivity per field of view, listed above, is based on noise measured with the shutter closed and response determined from measurements of known celestial sources. The noise when the shutter was open is somewhat above the shutter-closed values due to discrete source confusion. The nuclear radiation environment in orbit caused very little response change (<1%) in all detectors except the Ge:Ga photoconductors used at 60 and 100 μm. Thermal and radiative annealing procedures applied to these detectors following passages through the South Atlantic Anomaly allow response correction to about 1% at these wavelengths. It is expected that fully reduced DIRBE sky maps will have photometric consistency over the sky better than 2% at each wavelength, nearest-neighbor band-to-band (color) brightness accuracy of 3% or better, and absolute intensity scale accuracy better than 20%.

DIRBE Results. Preliminary results of the DIRBE have been described previously (12, 13, 101). Qualitatively, the initial DIRBE sky maps show the expected character of the infrared sky. For example, at 1.2 μm stellar emission from the galactic plane and from isolated high-latitude stars is prominent. Zodiacal scattered light from interplanetary dust is also prominent. These two components continue to dominate out to 3.4 μm, though both become fainter as wavelength increases. A composite of the 1.2, 2.3, and 3.4 μm images was presented by Mather *et al.* (6). Because extinction at these wavelengths is far less than in visible light, the disk and bulge stellar populations of the Milky Way are dramatically apparent in this image. At 12 and 25 μm, emission from the interplanetary dust dominates the sky brightness. As with the scattered zodiacal light, the sky brightness is strongly dependent upon ecliptic latitude and solar elongation angle. At wavelengths of 60 μm and longer, emission from the interstellar medium dominates the galactic brightness, and the interplanetary dust emission becomes progressively less apparent. The patchy infrared cirrus noted in IRAS data (102) is evident at all wavelengths longer than 25 μm.

The DIRBE data will clearly be a valuable new resource for studies of the interplanetary medium and Galaxy as well as the search for the CIB radiation.

In searching for the extragalactic infrared background, the most favorable conditions are directions and wavelengths of least foreground brightness. In general, because of the strong interplanetary dust foreground and the relatively modest gradient of that foreground over the sky, the infrared sky is faintest at high ecliptic latitude. A preliminary DIRBE spectrum of the sky brightness toward the south ecliptic pole was presented by Hauser *et al.* (101) and is reproduced in Table 1. This table shows the strong foreground from starlight and scattered sunlight at the shortest wavelengths, a relative minimum at 3.4 μm, emission dominated by interplanetary dust peaking around 12 μm, and generally falling brightness from there out to submillimeter wavelengths.

To meet the cosmological objective of measuring the CIB radiation, the foreground light from interplanetary and galactic sources must be discriminated from the total observed infrared sky brightness. This task requires extensive careful correlation studies and modeling, which in the case of the DIRBE investigation is in progress. A conservative upper limit on extragalactic light is the total observed brightness in a relatively dark direction. The sky brightness at the south ecliptic pole is a fair representation of the best current limits from the DIRBE. The faintest foregrounds occur at 3.4 μm, in the minimum between interplanetary dust scattering of sunlight and reemission of absorbed sunlight by the same dust, and longward of 100 μm, where interstellar dust emission begins to decrease. Through careful modeling, we hope to be able to discriminate isotropic residuals at a level as small as 1% of the foregrounds. These near-infrared and submillimeter windows will allow the most sensitive search for, or limits upon, the elusive CIB.

These data are to be compared with the theoretical estimates of contributions to the CIB radiation from pregalactic and protogalactic sources in a dust-free universe (e.g., ref. 89). The present conservative observational limits are beginning to constrain some of the theoretical models at short-infrared wavelengths, though in a dusty universe energy from these sources can be redistributed farther into the infrared. If the foreground components of emission can confidently be identified, the current COBE measurements will seriously constrain (or identify) the CIB radiation across the infrared spectrum. However, the spectral decade from about 6 to 60 μm will have relatively weak limits until measurements are made from outside the interplanetary dust cloud.

The CIB radiation promises to enhance our understanding of the epoch between decoupling and galaxy formation. The high quality and extensive new measurements of the absolute infrared sky brightness obtained with the DIRBE and FIRAS experiments on the COBE mission promise to allow a definitive search for this elusive background, limited primarily by the difficulty of distinguishing it from bright astrophysical foregrounds.

COBE Data Products and Plans

Extensive data products from the COBE mission consisting of calibrated maps and spectra with associated documentation are planned. The COBE databases have been described by White and Mather (103). An overview of the COBE software system has been given by Cheng (104). All COBE data processing and software development for analysis take place at the Cosmology Data Analysis Center (CDAC) in Greenbelt, MD, a facility developed by the COBE project for that purpose. This facility, and the software tools developed there, will become available to the scientific community when the data products are released.

Initial data products are planned for release in mid-1993. Galactic plane maps, including the nuclear bulge, will be available at all 10 DIRBE wavelengths and for the high-frequency FIRAS band. Full-sky maps from all six DMR radiometers will also be available.

Full-sky maps from all three COBE instruments, spanning four decades of wavelength, are planned for release in mid-1994. These data gathered by the COBE's three instruments will constitute a comprehensive data set unprecedented in scope and sensitivity for studies of cosmology and large-scale and solar system science.

Table 1. CIB limits as measured by DIRBE toward the south ecliptic pole

λ, μm	λI_λ, μW·m^{-2}·sr^{-1}
1.2	0.83 ± 0.33
2.3	0.35 ± 0.14
3.4	0.15 ± 0.06
4.9	0.37 ± 0.15
12	2.9 ± 1.2
22	2.1 ± 0.8
55	0.23 ± 0.1
96	0.12 ± 0.05
151	0.13 ± 0.07
241	0.07 ± 0.04

The authors gratefully acknowledge the contributions to this report by their colleagues on the COBE Science Working Group and the other participants in the COBE Project. Many people have made essential contributions to the success of COBE in all its stages, from conception and approval through hardware and software development, launch, flight operations, and data processing. To all these people, in government, universities, and industry, we extend our thanks and gratitude. In particular, we thank the large number of people at the Goddard Space Flight Center who brought this challenging in-house project to fruition.

1. Penzias, A. A. & Wilson, R. W. (1965) *Astrophys. J.* **142,** 419–421.
2. Mather, J., Thaddeus, P., Weiss, R., Muehlner, D., Wilkinson, D. T., Hauser, M. G. & Silverberg, R. F. (1974) *Cosmological Background Radiation Satellite,* NASA/Goddard Proposal (NASA, Greenbelt, MD).
3. Gulkis, S., Carpenter, R. L., Estabrook, F. B., Janssen, M. A., Johnston, E. J., Reid, M. S., Stelzried, C. T. & Wahlquist, H. D. (1974) *Cosmic Microwave Background Radiation Proposal,* NASA/JPL Proposal (NASA/JPL, Pasadena, CA).
4. Alvarez, L. W., Buffington, A., Gorenstein, M. V., Mast, T. S., Muller, R. A., Orth, C. D., Smoot, G. S., Thornton, D. D. & Welch, W. J. (1974) *Observational Cosmology: The Isotropy of the Primordial Black Body Radiation,* UCBSSL 556/75 Proposal to NASA (NASA, Greenbelt, MD).
5. Boggess, N., Mather, J. C., Weiss, R., Bennett, C. L., Cheng, E., Dwek, E., Gulkis, S., Hauser, M. G., Janssen, M. A., Kelsall, T., Meyer, S. S., Moseley, S. H., Murdock, T. L., Shafer, R. A., Silverberg, R. F., Smoot, G. F., Wilkinson, D. T. & Wright, E. L. (1992) *Astrophys. J.* **397,** 420–429.
6. Mather, J. C., Hauser, M. G., Bennett, C. L., Boggess, N. W., Cheng, E. S. *et al.* (1990) *Observatories in Earth Orbit and Beyond,* International Astronomical Union Colloquium no. 123, ed. Kondo, Y. (Kluwer, Boston), p. 9.
7. Mather, J. C., Hauser, M. G., Bennett, C. L., Boggess, N. W., Cheng, E. S., Eplee, R. E., Jr., Freudenreich, H. T., Isaacman, R. B., Kelsall, T. & Gulkis, S. (1991) *Adv. Space Res.* **11,** 181–191.
8. Mather, J. C. (1991) *Highlights Astron.,* 275–279.
9. Janssen, M. A. & Gulkis, S. (1992) *The Infrared and Submillimetre Sky After COBE,* eds. Signore, M. & Dupraz, C. (Kluwer, Dordrecht), p. 391.
10. Wright, E. L. (1991) *Ann. N.Y. Acad. Sci.* **647,** 190–198.
11. Wright, E. L. (1991) *The Infrared and Submillimetre Sky After COBE,* eds. Signore, M. & Dupraz, C. (Kluwer, Dordrecht), p. 231–248.
12. Hauser, M. G. (1991) *Proc. Infrared Astron. ISO, Les Houches, France,* 479–485.
13. Hauser, M. G. (1991) *Highlights Astron.,* 291–296.
14. Smoot, G. F., Bennett, C. L., Kogut, A., Aymon, J., Backus, C., De Amici, G., Galuk, K., Jackson, P. D., Keegstra, P. (1991) *AIP Conf. Proc.* **222,** 95–106.
15. Smoot, G. F. (1991) *Highlights Astron.,* 281–285.
16. Bennett, C. L. (1991) *Highlights Astron.,* 335–336.
17. Boggess, N. W. (1991) *Highlights Astron.,* 273–274.
18. Mather, J. C. (1982) *Opt. Eng.* **21,** 769–774.
19. Mather, J. C., Cheng, E. S., Shafer, R. A., Eplee, R. E., Isaac-

man, R. B., Fixsen, D. J., Read, S. M., Meyer, S. S., Weiss, R. & Wright, E. L. (1991) *AIP Conf. Proc.* **222**, 43–52.
20. Mather, J. C., Toral, M. & Hemmati, H. (1986) *Appl. Opt.* **25**, 2826–2830.
21. Mather, J. C. (1981) *Appl. Opt.* **20**, 3992–3993.
22. Mather, J. C. (1984) *Appl. Opt.* **23**, 584–588.
23. Mather, J. C. (1984) *Appl. Opt.* **23**, 3181–3183.
24. Mather, J. C. *et al.* (1990) *Astrophys. J.* **354**, L37–L41.
25. Gush, H. P., Halpern, M. & Wishnow, E. H. (1990) *Phys. Rev. Lett.* **65**, 537–540.
26. Matsumoto, T., Hayakawa, S., Matsuo, H., Murakami, H., Sato, S., Lange, A. E. & Richards, P. L. (1988) *Astrophys. J.* **329**, 567–571.
27. Shafer, R. A., Mather, J. C., Alexander, S., Bouler, D. B., Daffer, W. H. *et al.* (1991) *Bull. Am. Phys. Soc.* **36**, 1398.
28. Cheng, E. S., Mather, J. C., Shafer, R. A., Fixsen, D. J., Eplee, R. E., Jr., Isaacman, R. B., Read, S., Meyer, S. S. & Weiss, R. (1991) *Bull. Am. Astron. Soc.* **23**, 896.
29. Cheng, E. S., Mather, J. C., Shafer, R., Meyer, S., Weiss, R., Wright, E. L., Eplee, R., Isaacman, R. & Smoot, G. (1990) *Bull. Am. Phys. Soc.* **35**, 971.
30. Wright, E. L., Mather, J. C., Weiss, R., Bennett, C. L., Cheng, E. S. *et al.* (1991) *Astrophys. J.* **381**, 200–209.
31. Petuchowski, S. J. & Bennett, C. L. (1992) *Astrophys. J.* **391**, 137–140.
32. Sachs, R. K. & Wolfe, A. M. (1967) *Astrophys. J.* **147**, 73–90.
33. Guth, A. (1981) *Phys. Rev. D* **23**, 347–356.
34. Linde, A. (1982) *Phys. Lett. B* **108**, 389.
35. Albrecht, A. & Steinhardt, P. J. (1982) *Phys. Rev. Lett.* **48**, 1220–1223.
36. Bardeen, J. M., Steinhardt, P. J. & Turner, M. S. (1983) *Phys. Rev. D* **28**, 679–693.
37. Guth, A. & Pi, Y.-S. (1982) *Phys. Rev. Lett.* **49**, 1110–1113.
38. Hawking, S. (1982) *Phys. Lett. B* **115**, 295–297.
39. Starobinskii, A. A. (1982) *Phys. Lett. B* **117**, 175–178.
40. Bond, J. R. & Efstathiou, J. (1987) *Mon. Not. R. Astron. Soc.* **226**, 655–687.
41. Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A. & Kang, H.-S. (1991) *Astrophys. J.* **376**, 51–69.
42. Olive, K. A., Schramm, D. N., Steigman, G. & Walker, T. P. (1990) *Phys. Lett. B* **236**, 454–460.
43. Holtzman, J. A. (1989) *Astrophys. J. Suppl. Ser.* **71**, 1–24.
44. Peebles, P. J. E. & Wilkinson, D. T. (1968) *Phys. Rev.* **174**, 2168.
45. Smoot, G. F., Bennett, C. L., Kogut, A., Aymon, J., Backus, C. *et al.* (1991) *Astrophys. J.* **371**, L1–L5.
46. Smoot, G. F., Bennett, C. L., Kogut, A., Wright, E. L., Aymon, J. *et al.* (1992) *Astrophys. J.* **396**, L1–L5.
47. Bennett, C. L., Smoot, G. F., Janssen, M., Gulkis, S., Kogut, A., Hinshaw, G., Backus, C., Hauser, M. G., Mather, J. C. & Rokke, L. (1992) *Astrophys. J.* **391**, 466–482.
48. Kogut, A., Smoot, G. F., Bennett, C. L., Wright, E. L., Aymon, J., De Amici, G., Hinshaw, G., Jackson, P. D., Kaita, E. & Keegstra, P. (1992) *Astrophys. J.* **401**, 1–18.
49. Bennett, C. L., Smoot, G. F., Hinshaw, G., Wright, E. L., Kogut, A., De Amici, G., Meyer, S. S., Weiss, R., Wilkinson, D. T., Gulkis, S., Janssen, M., Boggess, N. W., Cheng, E. S., Hauser, M. G., Kelsall, T., Mather, J. C., Moseley, S. H., Jr., Murdock, T. L. & Silverberg, R. F. (1992) *Astrophys. J.* **396**, L7–L12.
50. Wright, E. L., Meyer, S. S., Bennett, C. L., Boggess, N. W., Cheng, E. S. *et al.* (1992) *Astrophys. J.* **396**, L13–L18.
51. Fixsen, D. J., Cheng, E. S. & Wilkinson, D. T. (1983) *Phys. Rev. Lett.* **50**, 620–622.
52. Lubin, P., Villela, T., Epstein, G. & Smoot, G. (1985) *Astrophys. J.* **298**, L1–L5.
53. Klypin, A. A., Sazhin, M. V., Strukov, I. A. & Skulachev, D. P. (1987) *Sov. Astron. Lett.* **13**, 104–107.
54. Meyer, S. S., Page, L. & Cheng, E. S. (1991) *Astrophys. J.* **371**, L7–L9.
55. Bertschinger, E., in *Current Topics in Astrofundamental Physics*, eds. Sanchez, N. & Zichini, Z., in press.
56. Bertschinger, E. (1992) in *New Insights into the Universe*, Proceedings of a Summer School, Valencia, Spain, September 23–27, 1991, eds. Martinez, V. J., Portilla, M. & Saez, D. (Springer, Berlin), pp. 65–126.
57. Efstathiou, G. (1990) in *Physics of the Early Universe*, eds. Peacock, J. A., Heavens, A. F. & Davies, A. T. (Edinburgh Univ. Press, Edinburgh, Scotland), pp. 361–463.
58. Kolb, E. & Turner, M. S. (1987) *The Early Universe* (Addison-Wesley, Redwood City, CA).
59. Peebles, P. J. E. (1971) *Physical Cosmology* (Princeton Univ. Press, Princeton).
60. Peebles, P. J. E. (1980) *The Large-Scale Structure of the Universe* (Princeton Univ. Press, Princeton).
61. Wilkinson, D. T. (1986) *Science* **232**, 1517–1522.
62. Smoot, G. F., Bennett, C., Weber, R., Maruschak, J., Ratliff, R. *et al.* (1990) *Astrophys. J.* **360**, 685–695.
63. Wright, E. L., Cheng, E. S., Dwek, E., Bennett, C. L., Boggess, N. W. *et al.* (1990) *Bull. Am. Astron. Soc.* **22**, 874.
64. Torres, S., Aymon, J., Backus, C., Bennett, C., Gulkis, S., Hollenhorst, R., Hon, D., Huang, Q. H., Janssen, M., Keihm, S., Olson, L., Smoot, G. & Wright, E. L. (1989) *Data Analysis in Astronomy*, Proceedings of a Conference held in Erice, Sicily, Italy, June 20–27, 1989, eds. di Gesu, V., Scarsi, L. & Maccarone, M. C. (Plenum, New York), pp. 319–334.
65. Franceschini, A., Toffolatti, L., Danese & De Zotti, G. (1989) *Astrophys. J.* **344**, 35–45.
66. Gorski, K. (1991) *Astrophys. J.* **370**, L5–L9.
67. Schaefer, R. K. (1991) *AIP Conf. Proc.* **222**, 119–122.
68. Gorski, K. M., Silk, J. & Vittorio, N. (1992) *Phys. Rev. Lett.* **68**, 733–736.
69. Efstathiou, G., Bond, J. R. & White, S. D. M. (1992) *Mon. Not. R. Astron. Soc.* **258**, 1P–6P.
70. Peebles, P. J. E. (1984) *Astrophys. J.* **284**, 439–444.
71. Peebles, P. J. E. (1991) *AIP Conf. Proc.* **222**, 3–11.
72. Davis, M., Summers, F. J. & Schlegel, D. (1992) *Nature (London)* **359**, 393–396.
73. van Dalen, A. & Schaefer, R. K. (1992) *Astrophys. J.* **398**, 33–42.
74. Gouda, N. & Sugiyama, N. (1992) *Astrophys. J.* **395**, L59–L63.
75. Vogeley, M. S., Park, C., Geller, M. J. & Huchra, J. P. (1992) *Astrophys. J.* **391**, L5–L8.
76. Loveday, J., Efstathiou, G., Peterson, B. A. & Maddox, S. J. (1992) *Astrophys. J.* **400**, L43–L46.
77. Hogan, C. J. (1991) *Nature (London)* **350**, 469–473.
78. Hogan, C. J. (1992) *Astrophys. J.* **398**, L77–L80.
79. Hogan, C. J. (1993) *Astrophys. J.* **403**, 445–449.
80. Hoyle, F. & Burbidge, G. (1992) *Astrophys. J.* **399**, L9–L10.
81. Bennett, D. P. & Rhie, S. H. (1992) preprint.
82. Partridge, R. B. & Peebles, P. J. E. (1967) *Astrophys. J.* **148**, 377–397.
83. Low, F. J. & Tucker, W. H. (1968) *Phys. Rev. Lett.* **21**, 1538–1541.
84. Peebles, P. J. E. (1969) *Philos. Trans. R. Soc. London A* **264**, 279–282.
85. Harwit, M. (1970) *Riv. Nuovo Cimento Soc. Ital. Fis.* **2**, 253–277.
86. Kaufman, M. (1976) *Astrophys. Space Sci.* **40**, 369–384.
87. Negroponte, J. (1986) *Mon. Not. R. Astron. Soc.* **222**, 19–36.
88. Fabbri, R. & Melchiorri, F. (1979) *Astron. Astrophys.* **78**, 376–378.
89. Bond, J. R., Carr, B. J. & Hogan, C. J. (1986) *Astrophys. J.* **306**, 428–450.
90. McDowell, J. C. (1986) *Mon. Not. R. Astron. Soc.* **223**, 763–786.
91. Fabbri, R., Andreani, P., Melchiorri, F. & Nisini, B. (1987) *Astrophys. J.* **315**, 12–27.
92. Fabbri, R. (1988) *Astrophys. J.* **334**, 6–13.
93. Bond, J. R., Carr, B. J. & Hogan, C. J. (1991) *Astrophys. J.* **367**, 420–434.
94. Murdock, T. L. & Price, S. D. (1985) *Astrophys. J.* **90**, 375–386.
95. Matsumoto, T., Akiba, M. & Murakami, H. (1988) *Astrophys. J.* **332**, 575–595.
96. Noda, M., Christov, V. V., Matsuhara, H., Matsumoto, T., Matsuura, S., Noguchi, K., Sato, S. & Murakami, H. (1992) *Astrophys. J.* **391**, 456–465.
97. Rowan-Robinson, M. (1986) *Mon. Not. R. Astron. Soc.* **219**, 737–749.
98. Magner, T. J. (1987) *Opt. Eng.* **26**, 264–269.
99. Evans, D. C. (1983) *Proc. Soc. Photo-Opt. Instrum. Eng.* **384**, 82–89.
100. Evans, D. C. & Breault, R. P. (1983) *Proc. Soc. Photo-Opt. Instrum. Eng.* **384**, 90–97.
101. Hauser, M. G. *et al.* (1991) *AIP Conf. Proc.* **222**, 161–178.
102. Low, F. J., Beintema, D. A., Gautier, T. N., Gillett, R. C., Beichman, C. A., Neugebauer, G., Young, E., Aumann, H. H., Boggess, N., Emerson, J. P., Habing, H. J., Hauser, M. G., Houch, J. R., Rowan-Robinson, M., Soifer, B. T., Walker, R. G. & Wesselius, P. R. (1984) *Astrophys. J.* **278**, L19–L22.
103. White, R. A. & Mather, J. C. (1991) *Astrophys. Space Sci. Libr.* **171**, 29–34.
104. Cheng, E. S. (1991) *First Annual Conference on Astronomical Data Analysis Software and Systems, Tucson, AZ, NOAO*, eds. Worrall, D. M., Biemesderfer, C. & Barnes, J. (Astron. Soc. Pacific, San Francisco), pp. 368–378.

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